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Why Schonland Failed in His Search for Runaway Electrons From Thunderstorms

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Key Points:

- Schonland's 1930s unsuccessful searches delayed progress in understanding runaway electrons from thunderstorms by several decades
- Thunderstorm ground enhancement (TGE) observations at two Mt. Aragats stations show limited possibility of detecting TGEs during thunderstorm season in Johannesburg in 1929

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Abstract B.F.J. Schonland, advised and encouraged by C.T.R. Wilson, made two unsuccessful searches for runaway electrons from thunderstorms in the 1930s. These findings stand in marked contrast with research results over the last decade and ironically set this field of research back many decades. Schonland's lack of success is traced to gamma ray attenuation in the atmosphere above Johannesburg (1,780 m MSL) and to his restriction to nine thunderstorms.

Plain Language Summary In the 1930s, B.F.J. Schonland tried to detect high-energy electrons from thunderstorms but failed due to the altitude of his observations and the limited sampling of thunderstorms. His unsuccessful attempts delayed progress in this field for decades, highlighting how much science has advanced since then.

1. Introduction

Nobel Prize winner C.T.R. Wilson, one of the first particle physicists and leading researcher of atmospheric electricity, recognized at the beginning of the last century that "the occurrence of exceptional electron encounters has no important effect on preventing the acquisition of large kinetic energy by particles in a strong accelerating field" (Wilson, 1925a). It was the first publication to introduce an enigmatic physical phenomenon of electron acceleration by the strong electric fields in thunderclouds called "runaway" electrons by A.S. Eddington (1926).

Of course, in 1925, the particle cascade theory was not yet established, the measurements of the electric field strength inside thunderclouds had not yet been achieved, and C.T.R. Wilson overestimated the scale of electron acceleration. He thought that electrons could gain unlimited energy from the electric field: "The general effect of an accelerating field is that a beta-particle, instead of dying as it were a natural death by gradual loss of energy, is continually acquiring more and more energy and increasing its chance of surviving all accidents other than direct encounters with the nuclei of atoms" (Wilson, 1925a) and "A particle may thus acquire energy corresponding to the greater part of the whole potential difference between the poles of the thundercloud, which may be of the order of 10^9 V" (Wilson, 1925b). However, that is impossible due to abundant radiation losses of electrons with energies greater than 50 MeV traversing the atmosphere. The tail of the first measured runaway electron spectrum in thunderstorm ground enhancements (TGEs) does not exceed 50 MeV (Chilingarian et al., 2010, 2011). A potential difference as large as 10^9 V also seems not feasible according to direct integrations of the vector electric field with balloon soundings (Stolzenburg & Marshall, 2008). Wilson's early estimates of thundercloud potentials were based on the assumption that the "sparking limit" at sea level conditions was 3×10^6 Vm.

By analyzing the abrupt changes in surface electric field accompanying intracloud and cloud-to-ground lightning flashes, Wilson (1916, 1920) established the basic positive dipole structure of the thunderstorm: positive charge in the upper part of the cloud and negative charge beneath it. This "model" was later confirmed by Schonland and Craib (1927) and by Schonland (1927) for thunderstorms in South Africa. In such a structure, free electrons are expected to accelerate downward beneath the main negative charge and to accelerate upward within the central dipole region of the storm. These two suspected source regions were considered separately in two experimental investigations by Schonland (1930) and Schonland and Viljoen (1933), respectively. Both studies were encouraged and followed by C.T.R. Wilson (Williams, 2010) through personal correspondence with Schonland, yet both searches are now considered largely unsuccessful.

Sixty years after these pioneering searches for runaway electrons, major puzzlements remained, as indicated in the following summary by Suszcynsky et al. (1996): "In summary and as an introduction to the present set of experiments, after 70 years of repeated theoretical and experimental investigations, it is still not clear whether or not the runaway electron acceleration mechanisms operate in a significant manner in either thunderstorms or lightning". In contrast to this somewhat pessimistic summary a quarter century ago, observations in the 21st century have repeatedly shown evidence for electron runaway in both regions of the Wilson thunderstorm dipole. The idea of Wilson that accelerated electrons can reach the upper atmosphere also finds support after the launch of the orbiting gamma ray observatories and balloon and aircraft flights (Marisaldi et al., 2024). Numerous terrestrial gamma flashes (TGFs) are routinely observed 500 km above Earth in correlation with strong equatorial thunderstorms (Fishman et al., 1994; Smith et al., 2005). The origin of these TGFs is believed to be the electrons accelerated upward in the main (upper) dipole, as Wilson suggested in 1925.

In recent years, there was significant progress in the detection of the particles (mostly gamma rays) from thunderclouds, both gamma-ray glows and TGEs. (Aglietta et al., 1989, 1999; Alexeenko et al., 2002; Brunetti et al., 2000; Eack et al., 2000; Enoto et al., 2017; Gurevich et al., 2004; Kelley et al., 2015; Kochkin et al., 2017; Kudela et al., 2017; Kuroda et al., 2016; Lidvansky, 2003; McCarthy & Parks, 1985; Moore et al., 2001; Ostgaard et al., 2019; Parks et al., 1981; Shaw, 1967; Shepetov et al., 2021; Torii et al., 2002, 2009, 2011; Tsuchiya et al., 2007, 2011, 2012; Wada et al., 2018, 2021).

In addition to the TGEs beneath thunderstorms and largely dominated by gamma rays, a smaller number of events at Aragats (Armenia) have been found that exhibit energetic electrons in addition to gamma rays (Chilingarian et al., 2023). The registration of TGE electrons and the recovery of their energy spectrum are crucial for supporting the relativistic runaway electron avalanches (RREA) model of enhanced fluxes. Different perspectives on these special events can be found in Chilingarian et al. (2023) and in Williams et al. (2023).

This essay considers both the experimental and conceptual shortcomings in Schonland's work, which prevented conspicuous positive results in the detection of relativistic runaway electron avalanches (RREA, Gurevich et al., 1992) and held up progress in this topic in the end of the 20th century.

Recognizing the same source for microsecond TGFs, minute-long gamma glows and TGEs mark a step toward accepting RREA as a universal physical process, and source for the enhanced particle fluxes in the lower and upper dipole. The subsequent terminology applies to the atmospheric fluxes of elementary particles produced during thunderstorms:

Terrestrial gamma-ray flashes (TGFs) are brief bursts of gamma radiation detected by orbiting gamma-ray observatories. They last for tens of microseconds, originate from thunderstorms at altitudes between 10 and 15 km in equatorial regions, and are identified by gamma-ray observatories positioned 400–700 km above the source.

TGEs (thunderstorm ground enhancements) refer to intense and prolonged particle fluxes observed on the Earth's surface, lasting up to several tens of minutes. These fluxes emerge from the same RREA process occurring within thunderclouds. However, the particle sources are in close proximity to the detectors (50–100 m), allowing for a detailed study of the energy spectra of electrons and gamma rays, the corresponding charge structures of thunderclouds, and the registration of fluxes from positrons and neutrons also arising from RREA.

Gamma glows are bursts of gamma radiation detected in the atmosphere by balloon or aircraft-based instruments. These events can last tens of seconds to several minutes and typically conclude with a lightning strike. The gamma-ray enhancements observed at the Earth's surface sometimes are also called gamma glows because, due to the high altitude of thunderclouds, they exclusively detect gamma rays and no other types of radiation particles.

Gamma glows, originating in upper atmospheric dipoles, exhibit different characteristics than TGEs. The high altitude, thinner air, and larger charges in the main positive layer of the upper atmosphere create distinct conditions for RREA development. Therefore, reserving the term "gamma glow" for particle fluxes observed in the upper atmosphere and "TGE" for particles observed on the Earth's surface is appropriate. Despite their different locations, these two phenomena—both powered by RREA—share similarities and would likely resemble each other if measured at the same distance from the source. Recent findings from the ALOFT mission support this conclusion (Marisaldi et al., 2024).

TGF was introduced in the 1990s to describe short bursts of gamma rays detected by satellites. TGF models propose that seed electrons originate not from cosmic rays but from streamers or lightning leaders. TGFs are rather an exotic phenomenon. Detecting microsecond-duration bursts of gamma rays by satellites positioned 400–700 km from their source provides limited information for physical analysis compared with the wealth of data gathered from TGEs and gamma glows. Moreover, the spatial resolution of TGF measurements is inherently lower due to the great distance between the "accelerator" and the detector, as opposed to TGE and gamma glow detectors.

2. The Initial Search Beneath Thunderstorms: Schonland (1930)

Schonland's education and research experience with electron scattering at the Cavendish Laboratory in the 1920s are key considerations in the ramp up to his initial search for runaway electrons with C.T.R. Wilson. This history is documented meticulously in a Schonland biography (Austin, 2001). Ernest Rutherford supervised Schonland's research work and communicated his findings (e.g., Schonland, 1925, 1926). Schonland became proficient in controlling the energy of cathode rays in the laboratory by deflection in magnetic fields (Schonland, 1925). The laboratory electron energies were limited to <100 keV (Schonland, 1926), in the region of monotonic decline of electron energy loss with increasing energy, according to the complete theory recognized today (Dwyer, 2004). This behavior was accordingly consistent with the assumptions made by Wilson (1925a) in his landmark paper on electron runaway.

During 1928, Schonland arranged to spend an entire year away from South Africa at the Cavendish Laboratory to work with Wilson on the "penetrating radiation" (Austin, 2001), the name given then to cosmic rays. Wilson conveyed to Schonland his ideas (e.g., Wilson, 1903) for a sensitive electroscope for ionization measurements based on his cloud chamber concepts (Wilson, 1927) involving ion pair production by energetic electrons. Schonland then constructed the ionization chamber (Schonland, 1929) to be used in the first search for runaway electrons in South Africa (Schonland, 1930).

As a most likely location in thunderstorms for electron runaway, Wilson gave consistent and repeated emphasis to the region above the main negative charge of the thunderstorm (Wilson, 1925a, 1925b, 1929), where the electric field was expected to be greatest and the air density to be reduced compared to like values beneath the storm. This interest is elaborated on in Section 3. Likely for practical reasons of accessibility, Schonland (1930) set out initially to explore the region directly beneath the thunderstorm for runaway electrons. Cognizant of Wilson's several published predictions (and documented above), Schonland wrote:

> "Since the fields which prevail in the majority of thunderclouds are directed downwards, an upward moving beam of runaway electrons is to be anticipated, passing into the upper air through the top of the cloud. A direct test of the existence of this beam would be very difficult, but it seemed probable that the effect could also serve in the upwardly directed or negative field between the base of the cloud and the ground. In this case, a downward-moving beam could be expected and might be detected by its ionizing action at the Earth's surface."

The new volume ionization chamber was used for this initial search, consistent with Wilson's (1925a) notion that the DC electric field of the cloud was responsible for accelerating the runaway electrons. The targeted quantity was the volume ionization rate in ion pairs per cc per second. The instrument design followed naturally from Wilson's (1927) Nobel-prize winning work on the counting of ion pairs in the tracks of ionizing particles with his expansion cloud chamber. The chamber was filled with CO_2 to increase its sensitivity to ionization, following the mass absorption law established from cosmic ray work. This device differed considerably from the event-based Geiger-Muller tube used later by Schonland and Viljoen (1933) in the second search for runaways. The change in voltage on the inner electrode was measured with a gold-leaf electrometer with enhanced sensitivity, based on Wilson's earlier experience with such instruments (Wilson, 1903), and required a tilting of the device to achieve maximum sensitivity in monitoring the small displacement of the gold-leaf. Some quantitative measure of the instrument's response was achieved through use of a standard gamma source, by noting its response to alpha particles, and by documenting the signal from the volume ionization afforded by cosmic rays (2.28 ion pairs/cc/sec).

Periods of intense electric field beneath South African thunderstorms (in Johannesburg, at an altitude of 1,780 m MSL), of both negative and positive polarity, were targeted with the ionization chamber. The normal negative polarity situations were named "A storms" and the less common positive polarity designated A'. No evidence for enhanced ionization was noted in either situation. In his summary, Schonland (1930) stated: "*A search was made for beams of downward moving "runaway" electrons in the negative fields below thunderclouds despite very favorable conditions, no such electrons could be detected…*"

Wilson revisited these negative results in a handwritten letter to Schonland on 9 June 1932, which would have been in the interval between the two tests. It is interesting that Wilson does not address any possible shortcomings in Schonland's measurement methods, but instead writes:

> "There may be no fast beta rays below the cloud on account of the field being too weak to accelerate them although a negative potential in the lower part of the cloud might approximate to 10^9 volts."

The stark contrast between Schonland's negative results in this initial search, and the great abundance of evidence for runaway electron in TGEs beneath thunderstorms over Mt. Aragats in Armenia is discussed in Section 4.1. See also Appendix A, where different detectors are also discussed.

3. The Second Search for Runaways Originating From the Central Dipole Region and Outside the Thunderstorm: Schonland and Viljoen (1933)

In a publication immediately following his seminal paper on electron runaway (Wilson, 1925a, 1925b) suggests a contribution from runaway electrons to "the penetrating radiation", known today as the cosmic radiation and, again focuses on the region above the storm:

> "At great height when the electric force is much reduced the deflecting action of the magnetic field becomes important, and the β rays will tend to run mainly along the magnetic lines of force."

Shortly thereafter, in a lecture invited by the Franklin Institute, Wilson (1929) is again emphasizing the central dipole region and the upper atmosphere:

> "There is then a possibility that ultra-beta particles from the region of maximum negative potential in a thundercloud may sometimes reach the upper atmosphere with a large part their energy unexpended. Any such electrons will describe helical paths of large radius around the magnetic lines of force and finally enter the lower atmosphere at widely separated parts of the Earth."

The idea in Wilson (1929) that the runaway electrons from thunderstorms might constitute the global "penetrating radiation" now known as cosmic rays led Hulburt (1931) to a theoretical test. He considered Larmor radii around terrestrial magnetic field lines for energies in the "electron spray" predicted by Wilson, and for possible thunderstorm sources at all latitudes. Hulburt's finding for reduced electron return at high latitude (where magnetic field lines did not return to connect with tropical thunderstorms) was inconsistent with the measured quasi-uniformity of cosmic rays with latitude.

All these ideas, as well as Schonland's laboratory experience with the deflection of cathode rays, clearly influenced the new search devised by Schonland and Viljoen (1933). They envisaged electrons accelerated up to 5 GeV energy in the central dipole region and rising out of the tops of thunderclouds to be deflected in the northward-directed magnetic field of the Earth into a Larmor radius R of ∼500 km to return to the Earth's surface in a quasi-circular arc of diameter 2R and ∼1,000 km east of the parent storm. Thus, the search had clearly moved from beneath the storm to storm-free locations far from the parent storm. For a range of electron energies, an electron "spray" was considered that could return to Earth over a range of distances out to a maximum of 1,000 km linked with a relativistic Larmor radius for 5 GeV electrons of 500 km in the local magnetic field of 3×10^{-5} T.

Cognizant of the fact that smaller electron energies, with associated smaller Larmor radii involved with the electron spray, Schonland and Viljoen (1933) searched for runaway electrons at the ground when storms were tens of km west of the measurement location. Without any mention of the ionization chamber used in the 1930 search, now a Geiger-Muller tube was to be used to detect ionization as discrete events, rather than continuously. This new instrumentation was in keeping with their strategy to "deal with the time relations between lightning strokes and (Geiger-Muller) counter impulses."

In a letter to Schonland on 9 June 1932, and prior to the publication of Schonland and Viljoen (1933), Wilson wrote:

> "The results you have been getting about coincidences between Geiger kicks and atmospherics from thunderstorms are very interesting. I can see no hole in them and if your further study the records has continued to show the effects, I think you should publish a note about them without delay."

The actual summary of the findings in Schonland and Viljoen (1933) reads as follows:

> "The observations show that some of the counter impulses are systematically coincident with lightning flashes"

These coincidences were few in number and no statistical analysis was included to substantiate a meaningful physical connection. Nor were these findings in Schonland (1930) and Schonland and Viljoen (1933) cited in later textbooks authored by Schonland (1950, 1953), nor in the final paper by Wilson (1956) in which runaway electrons are envisaged as a source for electron multiplication and negative charge for the giant influence machine. And both researchers went to their graves without convincing observational evidence for runaway electrons.

4. Discussion

Negative results in the evolution of science are often neglected along with explanations and implications that remain undocumented in the scientific literature. In the case of Schonland's negative results on runaway electrons, this re-examination is particularly instructive, especially given the lapse of nearly 80 years between the initial searches and the more recent breakthrough discoveries (e.g., Chilingarian et al., 2010; Fishman et al., 1994) pertaining to this phenomenon. Schonland's negative results in a search enthusiastically endorsed and monitored by C.T.R. Wilson set this field of research back for many decades and stand in stark contrast with present-day evidence for electron runaway, most notably at Mt. Aragats in Armenia (e.g., Chilingarian et al., 2011, 2012, 2017), and are the main motivation for this work.

4.1. Present Day Perspective on Schonland (1930)

Schonland (1930) made measurements beneath nine thunderstorms during a single thunderstorm season at Johannesburg, South Africa (1,780 m MSL). At Aragats in Armenia (3,200 m MSL), nearly every thunderstorm has been shown to produce a TGE with 277 events documented in a 5-year period (Chilingarian et al., 2013); now reaching nearly 1,000 well-documented observations on Aragats and mountaintops of Eastern Europe and Germany (Chilingarian, Karapetyan, Sargsyan, Aslanyan, & Chilingaryan, 2024; Chilingarian, Karapetyan, Sargsyan, Knapp, et al., 2024). But at a lower altitude station within the same mountains (Nor Amberd, 2,000 m MSL), the total number of TGEs was reduced to 20 in the same period, for an overall reduction factor of 20/277 = 7.2%. Further observations of events (Figure 1) recorded at Nor Amberd have shown the fraction of strong electric field-detected storm events (using an 8 kV/m threshold) as TGEs during one storm season in 2013 was 2 cases in 61, or 3.3% of the total.

If these same reduction statistics are applicable at a similar altitude at Johannesburg as for Schonland's search, then 7.2% of 9 storms (3.3% of 9) would have been detected with TGE status, with no confident expectation for any single event, consistent with Schonland's (1930) outcome.

It is now recognized, based on many observations of glows/TGEs in many locations and altitudes, that gamma rays are the predominant manifestation of electron runaway (Chilingarian, Hovsepyan, et al., 2024; Marisaldi et al., 2024; Wada et al., 2021; Williams et al., 2023). Accordingly, it is appropriate to consider Schonland's limitations in gamma ray reception during his 1930 search, in contrast to the numerous detections at Aragats in Armenia in recent years. Two key impediments are the layer of iron (10 mm thick) in the lid of the Wilson/Schonland ionization chamber and the layer of air between the Johannesburg altitude (1,780 m MSL) and the Aragats station (3,200 m MSL), amounting to 1,420 m. Comparative estimates of the contributions to mass attenuation coefficients are summarized in Table 1.

Since the mass per unit area (aka, column density) for the atmospheric lid exceeds that of the iron lid by a factor of 15, and the linear attenuation is exponentially dependent on the density x thickness product, the intervening atmosphere completely dominates the effect of the iron lid. This comparison also goes a long way toward explaining the large contrast in TGE incidence among Armenian observation sites at Aragats (3,200 m MSL), Nor Amberd (2,000 m MSL), and Yerevan (1,070 m MSL), discussed further in Section 4.3.

Extensive calculations of mass absorption coefficients in air have already been undertaken (Evans, 1955; Figure 1.2) over a range of photon energy from 0.01 to 100 MeV. The dominant loss mechanism in the relevant range of energy is Compton scattering of electrons followed by ion pair production by the electrons, which is the physical

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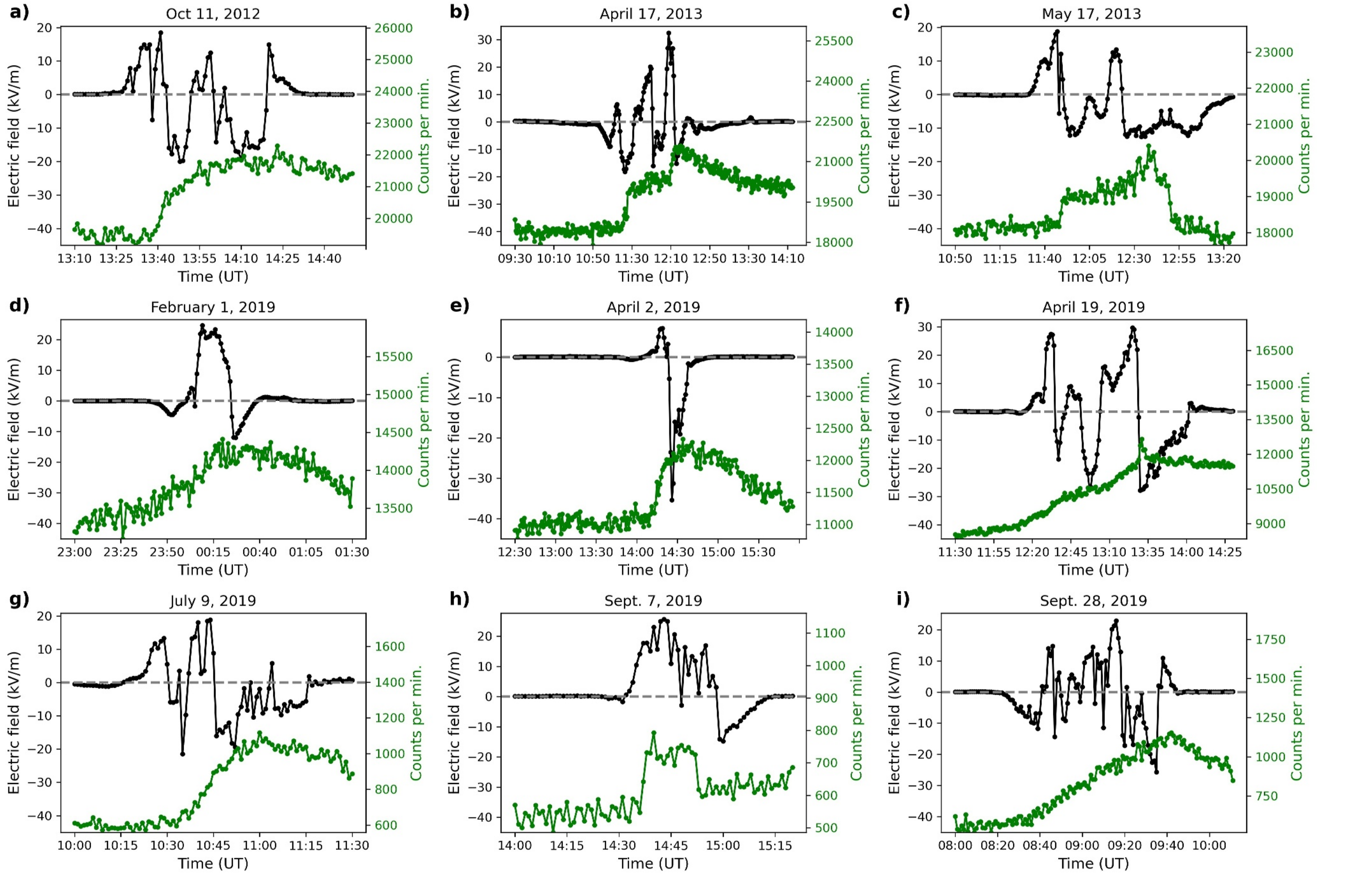

Figure 1. Selected thunderstorm records at Nor Amberd station, including simultaneous histories of Geiger-Muller flux and surface electric field. The radon signature identified by Chilingarian (2018) is characterized by smooth enhancement of count rate followed by decay with a half-time life controlled by ^{214}Pb and ^{214}Bi isotopes half-lifetime. The abrupt spikes followed by short-time enhancements are specific to a relativistic runaway electron avalanches process (like on 17 April 2013, 17 May 2013, and 7 September 2019).

basis of the ionization chamber devised by C.T.R. Wilson and used by Schonland (1930). Attenuation length (mean free path) estimates can be derived from these calculations of the mass absorption coefficient. Table 2 shows values as a function of gamma ray energy (MeV) over a range of energies typical for TGE detections in earlier studies.

4.2. Present Day Perspective on Schonland and Viljoen (1933)

Observations on Mt. Aragats in Armenia underway for more than a decade (see Appendix A) with particle detectors, electric field mills and an S-band radar at close range (22 km; Williams et al., 2022) have shown clearly that a necessary but not sufficient condition for the occurrence of a TGE indicative of runaway electrons is the presence of a strong (absolute value > 10 kV/m) near-surface electric field (NSEF) and the presence of a radar signal indicating the presence of ice-phase precipitation (i.e., graupel particles) over the detectors. No TGEs distant from thunderstorms in clear sky in the manner of Schonland and Viljoen (1933) have ever been detected. It is now recognized that runaway electrons produced in the central dipole region of thunderstorms could not escape directly to space because of losses in the dense atmosphere nor could they return to Earth along magnetic field lines in space for the same reasons. Energetic electrons cannot follow predicted Larmor radii in the dense troposphere. The Hulburt (1931) calculations discussed in Section 3 that inspired the design of the Schonland and Viljoen (1933) search were invalid in key locations.

Table 1
Contributions to Mass Attenuation From the Ionization Chamber and the Air Layer Over Johannesburg in Diminishing Gamma Ray Flux

	Iron lid	Atmospheric lid
Mean density	7.9×10^3 kg/m^3	8.4×10^{-1} kg/m^3
Thickness t	10^{-2} m	1.42×10^3 m
Density × thickness	79 kg/m^2	1,190 kg/m^2

The Geiger-Muller tube described in Schonland and Viljoen (1933) should have had adequate sensitivity to detect the enhanced gamma ray count rates

Table 2
Attenuation Lengths (i.e., e-Folding Distances) in the Air for Gamma Rays in the Energy Range Typical of Thunderstorm Ground Enhancement Detections Based on Mass Absorption Calculations in Evans (1955)

Energy (MeV)	Attenuation length (m)
0.5	126
1.0	169
2.0	238
5.0	400
10.0	526
20.0	625
50.0	717

Note. An air density (0.93 kg/m^3) typical of the altitude of Schonland's thunderstorm observations is assumed.).

typical of contemporaneously documented TGEs. This claim is substantiated by the simultaneous TGE registration by Geiger-Muller equipment and by plastic scintillator on Aragats and at Nor Amberd, in measurements beneath thunderstorms, as shown in detail in Appendix A.

Despite this second negative result by Schonland and colleagues to find runaway electrons on the ground at a large distance from thunderstorms, a success story for C.T.R. Wilson (1929) has emerged in its aftermath. Energetic electrons resulting from a runaway process in thunderstorms have been found spiraling around magnetic field lines as electron beams, extending from the storm source in one magnetic hemisphere to a satellite electron detector in the other hemisphere (Dwyer et al., 2008; Sarria et al., 2019). The distinction with the original concept in Wilson (1929) and Schonland and Viljoen (1933) is that, these energetic electrons are not runaways, but instead are the Compton scattered electrons from the gamma rays that in turn were produced by bremsstrahlung by the upwardly accelerated runaways within the main dipole of the parent storm. Furthermore, since these beam electrons will be strongly attenuated in the lower regions of the atmosphere where the magnetic field lines descend toward Earth, detections with surface measurements are unlikely.

In the final publication of his research career, Wilson (1956) showed exceptional insight in the aftermath of the negative results. He stated there:

> "*We have, however, to take into account the ionization due to the downward-moving electrons accelerated by the field (Wilson, 1925a, 1925b). The energy lost per centimeter of path, in producing ionization and radiation, is a minimum (about 2,000 eV at atmospheric pressure) for an electron of about 1 MeV. An accelerating field of one-tenth of the sparking value would thus be more than sufficient to compensate for the energy lost by such an electron. Its range may thus be greatly extended and its energy increased sufficiently to enable it to eject secondary electrons of energy required for acceleration by the field. Great multiplication of fast electrons may thus be affected by the field with corresponding increase of ionization.*"

4.3. The Role of Observer Altitude in the Detection of Electron Runaway

Sections 4.1 and 4.2 have compared the effect of the iron lid and the air layer above on the reception of gamma radiation. Here, we are concerned with the impact of the intervening atmosphere on the detected radiation at other locations (in comparison with Johannesburg) where TGEs have been documented.

The site of Schonland's (1930) measurements in Johannesburg, South Africa, stood at 1,780 m MSL. During summertime, when Schonland's measurements were carried out, the temperature-dependent height of the main negative charge in thunderstorms would have been at least 3,000 m above the observation location. This distance is more than five e-folding ranges for 10 MeV gamma rays and more than 50 e-folding ranges for 10 MeV electrons in air (Evans, 1955). These conditions place heavy limitations on the detectability of RREA-related TGEs at Johannesburg.

The foregoing expectations can be checked by examining summertime records at the Nor Amberd station, the sister site to Mt Aragats in Armenia. At 2,000 m MSL, Nor Amberd's altitude is slightly higher than Johannesburg's (1,780 m MSL).

Figure 1 shows a selection of Geiger-Muller tube records with simultaneously measured electric fields during overhead thunderstorms. The Geiger-Muller tube is of the same kind used by Schonland and Viljoen (1933). It has bandwidth for gamma ray energies (see Figure A-3 in Appendix A) suitable for the detection of both the lower energy gammas (<2 MeV) from radon progeny and the higher energy gammas (>5 MeV) linked with the RREA process.

Figure 1 shows that the radon signatures (Chilingarian, 2018; Chilingarian et al., 2019) are consistently present here with time scales commensurate with atmospheric electric field disturbances. In contrast, RREA-related TGEs with spikes of a few minutes in duration, which correlated with the enhancements in the electric field,

Table 3
Summary of Station Locations and Altitudes for Thunderstorm Ground Enhancement Documentation

Site Name	Latitude	Longitude	Elevation (m, MSL)
Aragats (Armenia)	40.47°N	44.18°E	3,200
Nor Amberd (Armenia)	40.37°N	44.26°E	2,000
Yerevan (Armenia)	40.18°N	44.51°E	1,070
Musala (Bulgaria)	42.11°N	23.35°E	2,925
Lomnický štít (Slovakia)	49.20°N	20.22°E	2,634
Milešovka (Czech Republic)	50.55°N	13.93°E	837
Zugspitze (Germany)	47.42°N	10.98°E	2,962
Zagreb (Croatia)	45.80°N	15.98°E	122
Hamburg (Germany)	53.55°N	10.00°E	6
Norikura (Japan)	36.11°N	137.55°E	2,770
Tibetan Plateau (China)	33.66°N	87.00°E	4,300
Tien Shan (Kazakhstan)	43.03°N	76.93°E	3,340
New Mexico (USA)	35.88°N	106.50°W	3,410
Vantaa (Finland)	60° 18’ N	24° 58’ E	55

were found for only three cases posted in Figure 1. Even at Nor Amberd, RREA TGE detection is highly infrequent compared with the higher station at Mt. Aragats, where the mean number of yearly TGEs exceeds 50.

TGEs have now been detected at many observatories worldwide, at locations and elevations summarized in Table 3, where we summarized the operational detectors that detect TGEs. Most of these station observation altitudes are greater than Johannesburg (1,780 m MSL) and Nor Amberd (2,000 m MSL). In interpreting the prevalence of TGE detections at any given station, it is important to consider the following: (a) The likely altitude of the source for gamma rays by electron runaway, (b) the impact of the intervening atmosphere in attenuating the gamma radiation from electron runaway (Table 2; Section 4.1), as well as (c) the statistics on TGEs, where they are prevalent (Aragats in Armenia) (Chilingarian, Sargsyan, et al., 2024; Chilingarian et al., 2013). The subfreezing temperature of the source region is important, given the evidence that collisions between ice particles in solid form (crystals and graupel) are needed for charge separation and subsequent gravitational separation to build the intense electric field. The statistics on the TGE amplitudes are important, given evidence for large numbers of small amplitudes, that increases in gamma radiation of only a few percent relative to the background cosmic radiation that is expected to disappear from detection with modest air attenuation (a single e folding distance, see Table 2) and the additional evidence for outstanding events that are hundreds of % (Chilingarian, Sargsyan, et al., 2024) and reaching 1,800% at Lomnicky Stit (Chum et al., 2020). Outstanding events at mountaintops can be explained by the proximity of the accelerating electric field to the detectors, the large electric field strength, and the site's geography. At Aragats, the thundercloud is sometimes so low over the station that the area becomes shrouded in thick fog. The sharp peak of Lomnicky Stit sometimes lies directly within the thundercloud inside the RREA. We need additional research with advanced instrumentation to measure the dynamics of electric field changes in the thunderclouds, and not only on the Earth's surface. However, the minute-long stability of enhanced particle flux discovered by (Chilingarian, Sargsyan, et al., 2024) indicates that yet unknown processes in the RREA stabilize the electron flux despite environmental changes occurring on a second-by-second scale.

The accumulated TGE detections at many locations and MSL altitudes in Table 3 can now be examined in light of the foregoing considerations. Stations with prevalent TGE detections (Aragats, Musala, Lomnicky Stit) have altitudes close to source regions, and source-detector separations of only several gamma attenuation lengths show at least 20 TGEs per year. In contrast, stations at low MSL altitudes and with large source-detector air gaps (many attenuation lengths) show few, if any, detections. Low-altitude sites at Zagreb (Hamburg) have produced zero TGE events in 15 (5) years. Two TGEs have been found at Yerevan in Armenia (1,070 m MSL) over a long monitoring period of 15 years. Wada et al. (2021, 2023) have documented many TGEs in Japan at sea level, but only in winter storms when the 0°C isotherm is much closer to the surface (Williams et al., 2023). Two TGEs were identified in Finland (55 m MSL) (Leppänen et al., 2024) in May during an episode of wet snow, suggestive again of a subfreezing source region close to the detectors.

The evidence for the key role of observer altitude on the detection of runaway electrons is further substantiated by the observations that frequent detections of TGEs are obtained at altitudes substantially higher than Schonland's (1930) Johannesburg (1,780 m). Examples from the recent literature are Aragats in Armenia (3,200 m MSL; Chilingarian, Sargsyan, et al., 2024), Mt. Norikura in Japan (2,770 m; Muraki et al., 2004), Lomnicky Stit in Slovakia (2,634 m; Chum et al., 2020; Chilingarian et al., 2021; Šlegl et al., 2022), the Zugspitze in Germany (2,650 m; Chilingarian, Karapetyan, Sargsyan, Knapp, et al., 2024), Tien Shan in Kazakhstan (3,340 m; Shepetov et al., 2021), and Yangbajing on the Tibetan Plateau in China (4,300 m; Tsuchiya et al., 2012). Additional observations of gamma ray glows during the ALOFT (Airborne Lightning Observatory for Fly's Eye Geostationary Lightning Mapper Simulator and Terrestrial Gamma Ray Flashes) campaign also demonstrate the influence of source-detector distance on event detectability (Marisaldi et al., 2024).

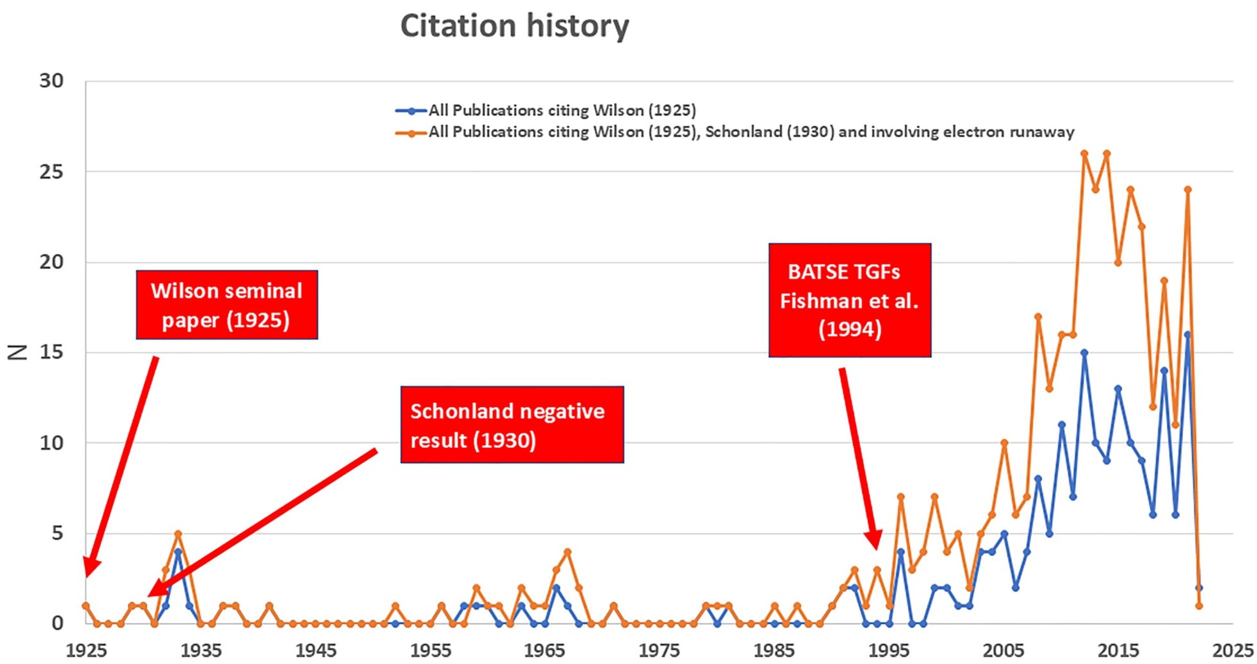

Figure 2. Publication history on runaway electrons (1925–2020). The literature checking was carried out through 2022.

4.4. Impact of Schonland Negative Results on High Energy Atmosphere Physics

Schonland's failure to find convincing evidence for C.T.R. Wilson's ideas on electron runaway had a rather profound and long-lasting effect on this field of research. This evidence is shown by the publication history in this field (Figure 2), following the seminal paper (Wilson, 1925a, 1925b). Here are shown the annual counts of all publications citing Wilson (1925a, 1925b) and a second tabulation of publications citing Schonland (1930) and also mentioning "electron runaway," organized by a research librarian at MIT. The publication trend is generally rather quiet for a period of more than 60 years following Schonland (1930) when Fishman et al. (1994) found evidence from the BATSE satellite for gamma rays of terrestrial origin. A major flood of papers followed with an order-of-magnitude increase in publication rate in less than 15 years.

5. Conclusions

Schonland searched for runaway electrons in two separate experiments. The initial search likely failed beneath South African thunderstorms because the altitude of Johannesburg (1,780 m) caused the gamma radiation from overhead storms to be sufficiently attenuated by the air layer between his ionization chamber and the high field region of the storms above and because only nine thunderstorms were examined. This conclusion is supported by comparative measurements of TGEs in Armenia, one at an altitude similar to Johannesburg (Nor Amberd, where TGEs are infrequent) and another at a substantially higher altitude (Aragats), where TGEs are common. Despite the use of an improved detector in Schonland's second search distant from thunderstorms, this search also failed because the highly collisional nature of electrons in atmospheric air was neglected, preventing a continuous electron trajectory from the main dipole to the Earth's surface along magnetic field lines as C.T.R. Wilson had envisaged.

Appendix A: Comparative Detector Measurements at Aragats

A1. Comparison of the TGE Registration by a Tray of Geiger Counters and a Plastic Scintillator Operated on Aragats

Since the initial detection of the Thunderstorm Ground Enhancement (TGE) on Aragats (Chilingarian et al., 2010, 2011), a strategy of multisensory detection for enhanced particle fluxes has been adopted. Various particle detectors, electric field sensors, meteorological instruments, atmospheric discharge sensors, lightning locators, and

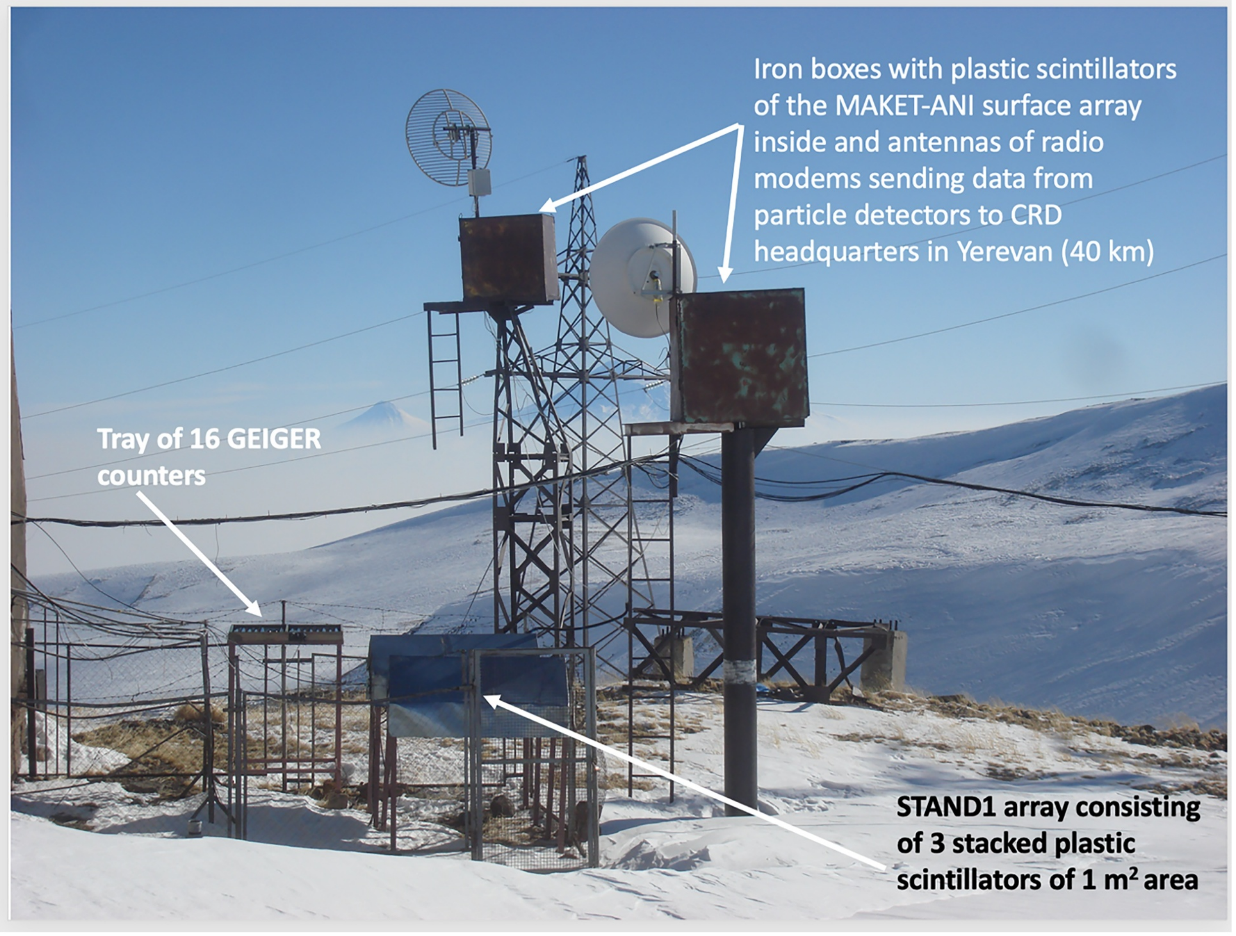

Figure A1. The experiment arrangement. A tray of 16 Geiger counters and STAND1 detector comprises 1 cm thick stacked plastic scintillators. Detectors were located outdoors to the west of the MAKET experimental hall.

optical cameras were used to thoroughly characterize TGE events and the environmental conditions from which they originate. In 2017, an experiment was planned to compare TGE registration with Geiger counters similar to the instruments used by Schonland and Viljoen (1933) and with counters made of plastic scintillators of varying thicknesses (1, 3, and 5 cm) and with the same area of 1 m^2.

A tray containing 16 CI5G type Geiger counters (length-60 cm, diameter-6 cm) was positioned outdoors, 5 m from the STAND1 detector, as depicted in Figure A1. STAND1 detectors consist of three vertically stacked plastic scintillators, each 1 cm thick and covering an area of 1 m^2 (we utilize the upper scintillator for comparisons). We must mention that Geiger counters detect gamma radiation not through direct interactions of gamma rays with the gas inside the detector (as its mass is negligible), but rather by registering Compton electrons produced when gamma rays interact with nearby passive materials. Consequently, their detection efficiency for gamma radiation is relatively low, typically just a few percent, as it strongly depends on the thickness and density of the surrounding passive material and the gamma-ray energy. Plastic scintillators detect gamma radiation primarily through Compton scattering and, at higher energies, via electron-positron pair production within the detector material. The detection efficiency strongly depends on gamma-ray energy and the scintillator thickness. Typical efficiencies range from about 2% to 3% for a scintillator thickness of 1 cm to approximately 50% for thicknesses of around 60 cm at energies where pair production dominates. The detectors operated continuously throughout 2017. Data were transmitted every minute to the Yerevan CRD headquarters via radio modem connections with antennas mounted atop masts that hosted iron boxes containing the plastic scintillators of the

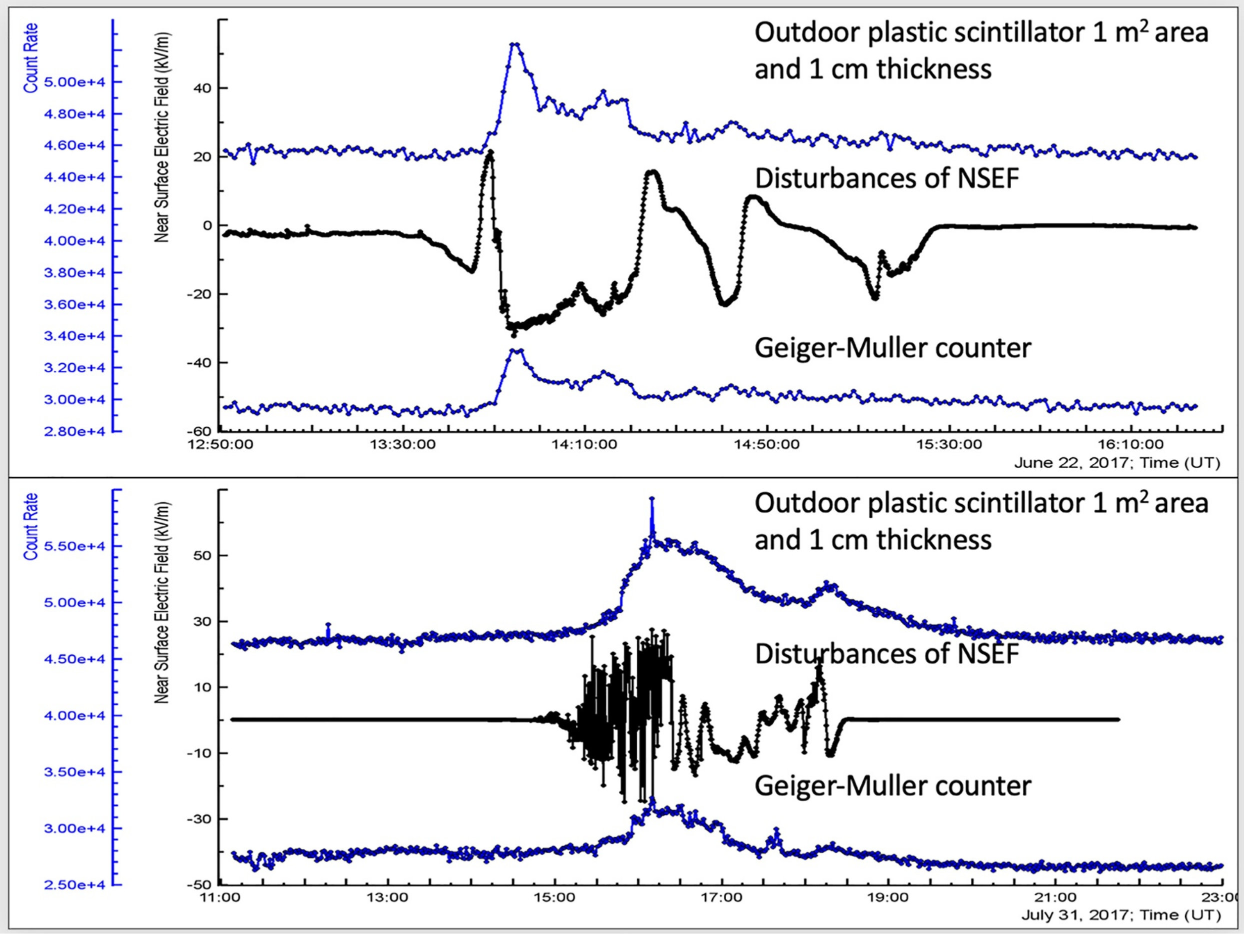

Figure A2. Upper blue curve—one-minute time-series of the count rate on the plastic scintillator; middle black curve—near-surface electric field disturbances measured by the electric mill (EFM-100) located on the roof of the MAKET experimental hall; lower blue curve one-minute time series of the tray of Geiger counters.

MAKET-ANI surface array. This setup measured the energy spectra of light and heavy galactic nuclei for the first time and confirmed supernova remnants as a source of PeV cosmic rays (Chilingarian et al., 2004, 2007).

In Figure A2, we show the detection of two TGEs by scintillators and Geiger counters that occurred on June 22 and 11 July 2017. The time series of both episodes of TGE detection precisely coincide. TGEs occur during large disturbances of the near-surface electric field (NSEF). The differences in the mean count rate measured before the TGE (30,000 and 46,300) can be explained by the sensitive area of the detectors (1 and 0.6 m^2) and by differences in energy thresholds and efficiencies for registering gamma rays and electrons.

In Figure A3, we compare the sensitivity of the Geiger detector and plastic scintillators of different thicknesses to charged and neutral particle fluxes. The highest peaks demonstrate the response of the Geiger counter and a 1 cm thick plastic scintillator. Outdoors, STAND1 and Geiger detectors (red and blue curves) demonstrate higher amplitude than indoors 3 cm thick STAND3 detector (green curve, Chilingarian & Hovsepyan, 2023), and 5-cm thick plastic scintillator of SEVAN detector (black curve, Chilingarian et al., 2018) with a higher energy threshold. Also, the SEVAN and STAND3 detectors are not sensitive to ^{222}Rn progeny gamma radiation, apparent in Geiger and STAND1 time series after 14:30.

Due to the radon circulation effect (Chilingarian et al., 2020), even small NSEF (1 kV/m and less) lifted aerosols with attached Radon and its progeny into the atmosphere. Subsequently, rain, if any, washes them out. A precise experiment was conducted on Aragats, proving the equivalence of isotope composition in the atmosphere and rainwater (Chilingarian & Sargsyan, 2024 for details). The "washout" effect was well known previously; see, for instance (Suszcynsky et al., 1996). However, we prove that the NSEF lifted aerosols with attached Radon progeny

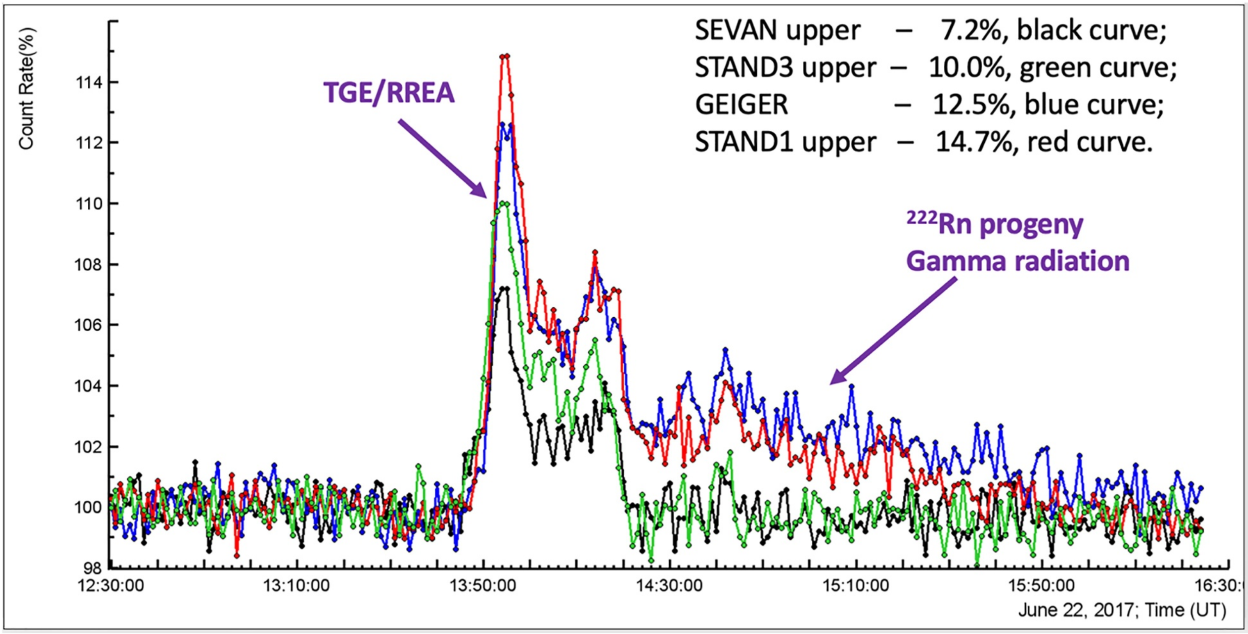

Figure A3. Detection of thunderstorm ground enhancement (we show in the body of the figure the maximum enhancement of count rate in percent) by Geiger and plastic scintillators. By the arrows, we show the two ingredients of the TGE: High energy and large amplitude enhancements originating by relativistic runaway electron avalanches and low energy prolonged enhancements due to gamma radiation of ^{222}Rn progenies lifted into the atmosphere by the near-surface electric field.

to the atmosphere, where they emitted gamma radiation in the low energy domain. Thus, only outdoor detectors having an energy threshold below 1 MeV registered prolonged gamma radiation from the decay of long-living isotopes ^{214}Pb and ^{214}Bi (the half-live 27 and 20 min, respectively).

Thus, in the 2017 experiment, we proved that Geiger counters (of the same type used in South Africa experiments) and the plastic scintillators used on Aragats efficiently register TGEs from RREA and from the Radon progeny radiation.

Data Availability Statement

The presented events data are available at adei.crd.yerphi.am. Selected TGE events are classified and stored in the Mendeley data sets (Chilingarian, Karapetyan, Aslanyan, & Sargsyan, 2024; Chilingarian, Karapetyan, Sargsyan, Aslanyan, & Chilingaryan, 2024). Moreover, data used to create Figure 1 have been uploaded to Figshare (Mkrtchyan, H. 2025).

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